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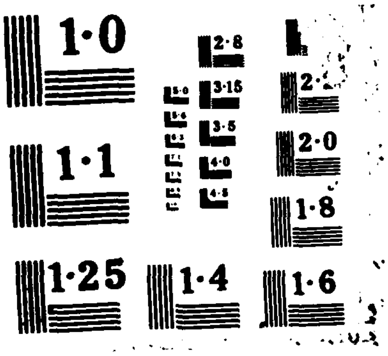
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The active cancellation of 2-dimensional laminar instability waves has been the subject of several recent investigations (Liepmann et al. 1982; Liepmann & Nosenchuck 1982; Thomas 1983; Gedney 1983). These experimental studies have demonstrated the feasibility of Tollmien-Schlichting (T-S) disturbance cancellation in flat plate boundary layers using a variety of active sources. Most recently, Birigen (1984) reported a numerical study which showed that significant reductions in amplitudes of two and three dimensional finite-amplitude disturbances can be obtained by the periodic application of suction and blowing in a plane channel flow. Liepmann and Nosenchuck (1982) used flush mounted hot element probes to sense T-S waves in a flat plate boundary layer and through a feed-forward loop introduced disturbances of equal amplitude but of opposite phase via flush mounted wall heaters to achieve significant delays of laminar to turbulent transition.

What is detailed herein is the first experimental study of the generation and cancellation of laminar-instability (T-S) waves by adaptive heat addition to a laminar boundary layer of an axisymmetric body. Tests were performed in a water tunnel environment on a 9:1 fineness ratio ellipsoid utilizing strip heaters to create and actively attenuate laminar instability waves. The attenuation signal was synthesized by a modified adaptive filter. The filter was able to actively adapt the attenuation signal to changes in amplitude and frequency of the instability wave with no loss in attenuation downstream.

Two important distinctives between Liepmann's work and the current study are the method of signal processing used and the introduction of three dimensionality in the flow. In our work the application of digital filtering techniques to the synthesis of the cancellation signal is unique. Further the flow geometry, although not a fully three dimensional, has elements of three dimensionality that further complicate the utilization of selective heat addition. The current experimental program has established that active heat addition controlled by a digital adaptive filter can successfully attenuate T-S waves in an axisymmetric geometry.

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Active control of 2-D instability waves on an axisymmetric body

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1 Introduction

The active cancellation of 2-dimensional laminar instability waves has been the subject of several recent investigations (Liepmann et al. 1982; Liepmann & Nosenchuck 1982; Thomas 1983; Gedney 1983). These experimental studies have demonstrated the feasibility of Tollmien-Schlichting (T-S) disturbance cancellation in flat plate boundary layers using a variety of active sources. Most recently, Birigen (1984) reported a numerical study which showed that significant reductions in amplitudes of two and three dimensional finite-amplitude disturbances can be obtained by the periodic application of suction and blowing in a plane channel flow. Liepmann and Nosenchuck (1982) used flush mounted hot element probes to sense T-S waves in a flat plate boundary layer and through a feedforward loop introduced disturbances of equal amplitude but of opposite phase via flush mounted wall heaters to achieve significant delays of laminar to turbulent transition.

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Two important distinctives between Liepmann's work and the current study are the method of signal processing used and the introduction of three dimensionality in the flow. In our work the application of digital filtering techniques to the synthesis of the cancellation signal is unique. Further the flow geometry, although not a fully three dimensional, has elements of three dimensionality that further complicate the utilization of selective heat addition. The current experimental program has established that active heat addition controlled by a digital adaptive filter can successfully attenuate T-S waves in an axisymmetric geometry.

2 Equipment and methods

The work was performed at the Naval Ocean Systems Center (NOSC) Hydromechanics Laboratory in the high speed water tunnel. The NOSC water tunnel facility has a 0.305 m diameter horizontal open jet test section which can accommodate models up to 0.75 m in length. Water velocities up to 14 m/sec can be achieved with a free stream turbulence level (u'/u_∞) of 0.16% throughout the speed range.

The model used was a sting mounted 9:1 fineness ratio ellipsoid of revolution. A complete description of the model used in these tests is contained in Whittier (1984). The body maximum diameter was 50 mm. The body maintained a true elliptical outline until an axial distance of 397 mm where the radius assumed a constant slope to intercept the sting diameter of 25.4 mm. Velocity perturbations were introduced into the boundary layer with ring heaters (oriented across the flow) located at $x = 40$, 44 and 53 mm, where x is the axial distance from the nose. The effect of the heaters is to periodically change the local viscosity in the boundary layer in order to introduce the desired velocity perturbation. Other methods should be equally effective (i.e. periodic suction or wall movement), however the periodic heating scheme appeared to be the easiest to implement. Three hot film type shear stress

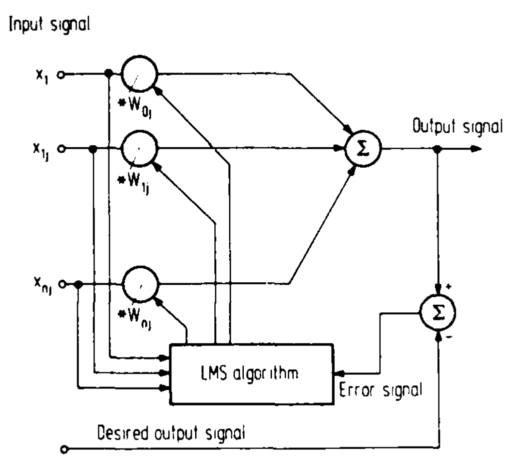

Fig. 1. Schematic of adaptive algorithm/linear combiner

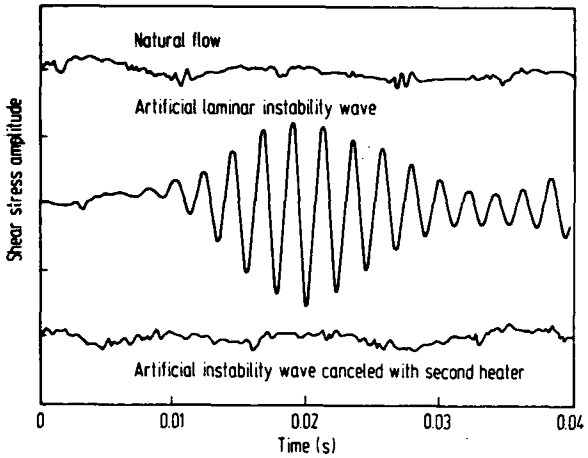

Fig. 2. Attenuation of artificial instability waves

probes were flush mounted at an axial location of 130 mm. The hot films were located at tangential positions of 0, 90 and 180 degrees from the top of the model.

An adaptive filter was used to actively control the boundary layer heaters in order to minimize the growth of the T-S waves. The adaptive signal processing was done with a microprocessor based system which utilized a modified Widrow-Hoff Least Mean Square (LMS) algorithm (an excellent brief description of the LMS adaptive algorithm is contained in Widrow et al. 1975). Simply stated the purpose of the adaptive algorithm in an adaptive filter is to adjust the weights of the linear combiner (Fig. 1) to minimize mean-square error and arrive at the optimal weight vector.

3 Results

The foremost ring heater was used to force formation of instability waves in the laminar flow boundary layer of the ellipsoid. The adaptive filter, based on the reference signal from the forward heater and an error signal from one of the downstream shear probes, then synthesized an input to the attenuation heater that effectively cancelled the artificially generated wave packets.

The first trace in Fig. 2 shows typical output from the top shear stress probe, $x = 130$ mm, with all heaters inoperative. The freestream velocity for this test was about 4.5 m/s. This small amount of fluctuation in the velocity signal could be due to background turbulence or the beginnings of some small instability wave packets.

Trace 2 shows an instability wave packet generated by using the foremost heater operated at 465 Hz. During the tests, instability waves were generated at a variety of frequencies within the expected unstable frequency range.

Trace 3 is the output from the shear stress probe when both the T-S wave forcing heater and the adaptively driven attenuation heater are operating. Comparison of trace 1 with trace 3 shows little difference between the flow in "natural" conditions and the flow with created and then cancelled waves, indicating a high degree of attenuation of the forced instability wave.

The adaptation time of the filter was typically on the order of a fraction of a second. Further the filter was able to actively adapt to changes in forcing frequency and amplitude of the foremost heater with no changes in the amount of attenuation downstream.

4 Discussion

What has been demonstrated is the adaptive filter's ability to actively attenuate an artificial, largely two dimensional instability wave and to adapt to changes in frequency and amplitude in that wave what remains to be examined is its ability to attenuate naturally occurring waves and thereby delay the transition process.

Measurements of naturally occurring waves on the ellipsoid, not reported here, have shown that the natural waves are highly three dimensional. Whether this is due to the axisymmetric geometry or the free stream turbulence level is not apparent. What is apparent is that the asymmetry and varying amplification rates of the natural instability waves makes the task of active cancellation of natural waves on an axisymmetric body much more difficult than those artificially generated in the present study or those naturally occuring on a flate plate. The planned approach is to utilize an upstream shear stress probe, relatively close to the active cancellation heater as the reference signal for the adaptive filter, with a second sensor downstream to measure the "error" signal. Additionally, the ring heaters will be segmented around the circumference of the model and operated independently by a separate active controller.

Acknowledgements

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